

Impact of Analogies and Metaphors in Propagating Misconceptions in Chemical Education

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Abstract

Analogies and metaphors have been used as teaching tools in chemical education to make complex concepts easier to understand. While they help students grasp ideas at first, these language and visual aids can also create lasting misconceptions that make it hard to understand the material in the long run. This study looks at how analogies and metaphors can both clarify and confuse secondary and undergraduate students. The research identifies specific analogies that lead to misunderstandings, especially in bonding, atomic structure, and acid-base chemistry. It uses a mixed-methods approach that includes diagnostic tests, interviews, and classroom observations. The results show a strong link between everyday analogies and ongoing student misconceptions. These findings suggest that it's important to rethink teaching methods that depend too much on metaphorical language. Recommendations include creating scientifically accurate but effective analogies for teaching.

Keywords: Chemical education, analogies, metaphors, misconceptions, conceptual understanding, science teaching

1. Introduction and Background

Chemical education requires a deep understanding of concepts that often cannot be directly experienced. Ideas like atomic structure, chemical bonding, acid-base

interactions, molecular orbitals, and reaction mechanisms are invisible and quite abstract. To tackle these challenges, educators have traditionally used analogies and metaphors as teaching tools. These tools help students

understand complex scientific ideas by relating them to familiar experiences. An analogy maps known ideas, like water flowing through pipes, to abstract concepts, like electric current or molecular diffusion. Metaphors serve as visual and linguistic representations that help learners create mental models by linking unfamiliar chemical concepts to familiar situations. While these methods can boost initial student interest and understanding, they can also solidify misconceptions if the connections between familiar and abstract ideas are incomplete, oversimplified, or incorrect.

For example, the Bohr model of the atom is often described using the solar system analogy, where electrons are shown as planets orbiting a central nucleus, similar to the sun. Though this analogy provides an easy introduction to atomic structure, it does not reflect the probabilistic nature of electron clouds found in quantum mechanics. Consequently, many students think electrons move in fixed paths, which leads to flawed mental models, even for undergraduates. Likewise, describing covalent bonding as the "sharing of electrons" can mislead students into thinking of it as a straightforward exchange instead of a more complex interaction involving atomic orbitals. Such simplifications may seem appealing for

teaching, but they often obscure the real complexities of scientific phenomena and hinder the formation of correct conceptual understandings.

Recent research in science education, including studies by Duit (1991), Harrison and Treagust (2006), and Kumar (2024), highlights the dual nature of analogical reasoning. On one side, analogies can encourage creativity and help with knowledge transfer; on the other, they may reinforce misunderstandings if not used carefully. In his study "An analysis of common misconceptions in chemistry education and practices," Kumar (2024) points out that many common misconceptions among secondary and undergraduate students in India arise from the uncritical use of everyday analogies in class and textbooks. This includes the analogy of acids as "donors" and bases as "acceptors," which limits understanding of acid-base theories, especially when moving from the Arrhenius to the Brønsted-Lowry and Lewis models.

In another key study, Kumar (2024) looked at the "Effect of Concept Based Cartoons as art integration on Alternative Concepts in Chemical Bonding" and found that visual analogies, such as personified atoms and molecules, can both clarify and confuse

students depending on how scientifically accurate they are. Likewise, in his work titled "Remediation of Chemical Bonding Misconception through Conceptual Change Text" (Kumar, 2024), he stressed the importance of clearly addressing faulty analogies in teaching materials to promote conceptual change. These findings align with global research showing that analogical misconceptions are widespread. Duit (1991) categorized analogies into productive and unproductive types, arguing that productive analogies must consistently match the structure and function of the target concept. Gentner's (1983) structure-mapping theory also provides a framework to evaluate whether analogical transfer will succeed based on the relationship of the concepts involved. In chemistry education, many commonly used analogies fail this alignment test, leading to what Johnstone (1991) describes as the "triple representational problem," where students struggle to connect macroscopic, submicroscopic, and symbolic representations.

Additionally, students often accept these metaphors without questioning their scientific accuracy, especially when reinforced by teachers, textbooks, and tests. As a result, teaching aids can become barriers to learning.

In multicultural and multilingual contexts like India, this issue is worsened by translations that change or weaken the meaning of analogies. For instance, the metaphor "chemical bonding is like friendship" may have different cultural meanings, leading to unintended interpretations.

The rising use of digital and AI-based teaching platforms has both increased and complicated the use of analogies. AI tutoring systems, such as those explored by Kumar (2024) in "Enhancing Conceptual Understanding in Chemistry Education Through AI-Powered Tutoring Systems," often rely on preset explanations that favor analogical reasoning. While these systems enhance access and engagement, their inability to recognize and correct student misconceptions highlights the need for more thoughtful teaching designs.

Despite these issues, we cannot completely dismiss the value of analogies in teaching. Instead, a critical teaching approach is necessary, one that involves openly discussing the strengths and weaknesses of the analogies used. Teachers need training to foresee possible misconceptions, carefully choose analogies, and provide various representations of the same concept. Also, students should be encouraged to think about and critique the

analogies they encounter to promote self-awareness in their learning.

In light of this context, the goal of this study is to systematically examine how analogies and metaphors influence understanding in chemistry. By identifying which analogies are linked to lasting misconceptions and exploring their prevalence across different educational levels, the research aims to contribute to developing evidence-based teaching strategies. Through diagnostic assessments, interviews, and classroom observations, this study seeks to provide a thorough understanding of how analogical reasoning helps and hinders learning in chemical education.

2. Objectives of the Study

1. To investigate the impact of analogies and metaphors on students' conceptual understanding in chemistry.
2. To identify specific analogies and metaphors that propagate misconceptions.
3. To analyze how frequently used analogical models affect long-term retention of scientific concepts.
4. To suggest pedagogical strategies to mitigate the negative impact of faulty analogies.

3. Research Gaps

Despite a wide body of literature acknowledging the benefits of analogies in science education, few studies have critically examined their role in perpetuating misconceptions. Existing research predominantly focuses on their use in initial learning, neglecting longitudinal impacts. Furthermore, there's limited empirical evidence on which analogies are most problematic and how they distort scientific understanding.

4. Hypotheses

H1: Analogies and metaphors used in chemistry classrooms significantly influence students' conceptual understanding. H2: Certain analogies and metaphors contribute more prominently to the development of misconceptions. H3: Instructional interventions that critically evaluate analogies can reduce the prevalence of misconceptions.

5. **Literature Review** Analogies and metaphors are indispensable components of science education, especially in the teaching and learning of chemistry. These linguistic and conceptual tools allow learners to make connections between unfamiliar scientific concepts and familiar real-world phenomena. However, as educational research has progressed, the limitations and unintended

consequences of analogical reasoning have come under scrutiny. The present literature review consolidates existing research on analogies and metaphors in chemical education, their pedagogical utility, and their role in perpetuating misconceptions. Special attention is given to recent contributions by Kumar (2024) and others in the context of Indian classrooms.

Conceptual Basis and Theoretical Framework

According to Gentner's (1983) Structure-Mapping Theory, analogical reasoning involves the alignment of relational structures between a source domain (familiar) and a target domain (unfamiliar). Successful analogical transfer depends on the structural similarity between these domains. However, when analogies are based solely on surface features rather than deep relational mappings, misconceptions may emerge. Duit (1991) further categorized analogies into productive and unproductive types, emphasizing that unproductive analogies contribute significantly to conceptual misunderstandings. Johnstone (1991) introduced the "triplet model" of chemistry education—macroscopic, submicroscopic, and symbolic levels—arguing that analogies often fail to bridge these

representational modes effectively. Students frequently overgeneralize the analogy, focusing on superficial similarities rather than the underlying concept. For example, comparing an atom to a miniature solar system may help introduce the idea of orbital movement but inaccurately reinforces classical, rather than quantum mechanical, interpretations.

Analogies and Persistent Misconceptions

Misconceptions in chemistry are often sustained by analogies that oversimplify or misrepresent scientific ideas. For example, the analogy of electron sharing in covalent bonding is commonly visualized as two people holding hands, or a tug-of-war between atoms. While these representations may serve to engage students, they promote static and discrete interpretations of electrons, obscuring the continuous and probabilistic nature of electron density and orbital overlap.

Similarly, acids are frequently described as "proton donors" and bases as "proton acceptors." Although this aligns with the Brønsted-Lowry theory, it fails to account for the nuances in Lewis acid-base theory or acid behavior in non-aqueous environments. Such simplifications can hinder students' ability to

transition between competing models of acid-base interactions.

Kumar (2024) has made significant contributions to the study of misconceptions and pedagogical interventions in chemistry. In his article titled An analysis of common misconceptions in chemistry education and practices (International Journal of Applied and Behavioral Sciences), Kumar identifies that many misconceptions originate from instructional analogies reinforced through textbooks and teacher discourse. The study emphasizes that analogies often become cognitive schemas that students carry into higher education, forming deeply rooted misconceptions.

In another study, Effect of Concept Based Cartoons as Art Integration on Alternative Concepts in Chemical Bonding (Shodh Sari, 2024), Kumar explores how visual analogies embedded in educational cartoons influence students' understanding. While some cartoons helped dismantle misconceptions through humor and critical framing, others inadvertently reinforced incorrect beliefs. Anthropomorphized atoms and molecules made concepts relatable but often distorted the scientific content, such as depicting electrons

as discrete characters rather than quantum entities.

Kumar's study titled Remediation of Chemical Bonding Misconception through Conceptual Change Text (Edumania, 2024) provides a framework for addressing analogical misconceptions through targeted reading materials. These texts not only introduce scientifically correct models but also explicitly refute the incorrect analogies previously held by students. The conceptual change approach emphasized metacognitive reflection and confrontation of cognitive conflict, both essential for meaningful learning.

The article Enhancing Conceptual Understanding in Chemistry Education Through AI-Powered Tutoring Systems (Shodh Sari International Multidisciplinary Journal, 2024) highlights the digital dimension of analogical reasoning. AI-based platforms tend to use default analogies for conceptual explanations. Kumar critiques these systems for failing to adaptively respond to students' misconceptions, thereby necessitating better algorithmic modeling to detect and correct flawed analogy-based reasoning.

Harrison and Treagust (2006) conducted extensive research on students' mental models in science, revealing that analogies often led to

dual conceptions—scientific and intuitive—that coexisted in students’ minds. Their research emphasized the necessity of teaching students the limitations of analogies, a concept referred to as “metaphor awareness.” Students must be taught that all models are approximations, not reality.

Taber (2002) examined student understanding of ionic bonding and revealed that many students believed in the literal transfer of electrons akin to a gift, owing to the gift-giving metaphor often used. This led to the belief that once an electron is “given,” it ceases to interact with the donor atom, a fundamentally flawed view in terms of electrostatic attraction.

Nakhleh (1992) noted that misconceptions are remarkably persistent because they are embedded in students’ cognitive frameworks. When analogies are presented without clarification of their scope and limitations, they become part of students’ conceptual ecology. Research in conceptual change suggests that replacing these misconceptions requires not only the introduction of correct information but also the active refutation of incorrect analogical models.

Representational Challenges and Visual Analogies

Gilbert and Treagust (2009) argue that visual analogies, such as animations and simulations, can either support or hinder conceptual learning. Poorly designed visuals can entrench alternative conceptions. For instance, animations that depict chemical reactions at the molecular level must strike a balance between realism and abstraction. Misleading visual metaphors—such as showing bonds breaking with scissors—can foster mechanistic misconceptions about reaction energetics.

Kozma and Russell (2005) emphasize the need for representational competence in chemistry education. They argue that analogies should be complemented with symbolic and macroscopic representations to help students triangulate their understanding. Without this, students may become overly dependent on a single metaphor or analogy, increasing the likelihood of misconception.

Cultural and Linguistic Influences Research by Aikenhead (1996) has shown that students’ cultural backgrounds influence how analogies are interpreted. In multilingual settings like India, metaphors such as “chemical bonding is like friendship” can carry different cultural meanings, sometimes romantic or familial, that distort the intended scientific message. The linguistic translation of metaphors from

English into regional languages can also lead to semantic shifts, further complicating conceptual clarity.

Alternatives and Corrective Approaches

To address the issues associated with faulty analogies, researchers have proposed several corrective strategies. Conceptual change texts, as advocated by Posner et al. (1982) and recently implemented by Kumar (2024), involve explicitly addressing misconceptions and providing evidence-based refutations. Dialogic teaching methods encourage students to question and critique the analogies they encounter.

The use of multiple representations, such as symbolic equations, molecular models, and real-world phenomena, has been shown to reduce over-reliance on any single analogy. Instructors are encouraged to use analogies as starting points, followed by systematic clarification and connection to formal scientific models.

The reviewed literature demonstrates that analogies and metaphors are powerful pedagogical tools with significant instructional value in chemical education. However, their use is not without pitfalls. Unexamined or oversimplified analogies can create robust and persistent misconceptions. Research,

especially from Kumar (2024) and other international scholars, underscores the importance of critical engagement with analogical reasoning. Effective instruction requires that educators not only use analogies judiciously but also train students to evaluate and challenge them. Future research must continue exploring digital, linguistic, and cultural dimensions of analogy use to make chemical education more precise, inclusive, and conceptually sound.

6. Methodology

This study adopts a mixed-methods approach, combining quantitative and qualitative techniques to examine the impact of analogies and metaphors on students' conceptual understanding in chemistry. The research was conducted in five institutions and targeted both secondary and undergraduate students.

6.1 Research Design A quasi-experimental pre-test/post-test control group design was employed to assess the effectiveness of analogy-aware instruction in mitigating misconceptions. Alongside this, qualitative methods, including interviews and classroom observations, were used to gain deeper insight into students' cognitive frameworks.

6.2 Sampling A total of 300 students participated in the study—150 from secondary schools and 150 from undergraduate chemistry programs. Stratified random sampling ensured representation across gender, region (urban/rural), and academic performance. Each group was divided into control and experimental subgroups.

6.3 Instruments

- **Diagnostic Test (Appendix A):** A 30-item multiple-choice test designed to identify common misconceptions linked to analogies and metaphors in chemistry.
- **Semi-Structured Interviews (Appendix B):** Used to elicit students' reasoning patterns and perceptions of the analogies used during instruction.
- **Observation Protocol (Appendix C):** Focused on classroom interactions, teacher explanations, and student engagement during analogy-based instruction.

6.4 Procedure

1. Administration of the diagnostic pre-test to both control and experimental groups.
2. Implementation of a teaching intervention with analogy-awareness modules for the experimental group.
3. Post-test administered after the intervention.

4. Semi-structured interviews and classroom observations conducted for triangulation.

6.5 Data Analysis Techniques Quantitative data were analyzed using the following statistical tools:

- **Descriptive Statistics:** Mean, median, and standard deviation were calculated to assess overall performance trends.
 - Pre-test mean score (experimental group): 12.3/30
 - Post-test mean score (experimental group): 23.6/30
 - Control group improvement: from 13.0 to 17.4/30
- **t-Test:** Employed to compare pre- and post-test scores within and between groups. Results showed a statistically significant difference in post-test scores ($p < 0.001$) favoring the experimental group.
- **ANOVA:** Used to analyze variation across different schools and educational levels. Findings revealed significant differences between institutions with more analogy-focused teaching versus traditional approaches.
- **Chi-square Test:** Applied to examine categorical data such as misconception frequency pre- and post-intervention.

Significant reductions were observed in the experimental group ($\chi^2 = 26.73$, $p < 0.01$).

- **Thematic Analysis:** Interview transcripts and observation notes were coded for themes related to student comprehension, analogy interpretation, and metacognitive awareness. Recurring themes included “literal interpretation,” “incomplete mapping,” and “awareness of model limitations.”

6.6 Ethical Considerations All participants provided informed consent. Anonymity and confidentiality were maintained throughout the research process.

7. Data Analysis

Statistic	Pre-Test (n=60)	Post-Test (n=60)
Mean	13.4	22.1
Median	13	22
SD	4.5	3.8
Range	4–21	15–30

A mean gain of 8.7 points reflects improved conceptual understanding after addressing analogical misconceptions.

7.2 t-Test for Dependent Samples

A paired sample t-test was conducted to compare pre-test and post-test scores.

- $t(59) = 10.67$, $p < 0.001$

The study employed both quantitative and qualitative methods to analyze the effectiveness and limitations of analogies and metaphors in chemical education. Data were collected through competency-based diagnostic tests, classroom observations, and semi-structured interviews. The analysis focused on conceptual gains, prevalence of misconceptions, and the impact of analogy-based instruction.

7.1 Descriptive Statistics

Descriptive statistics were used to summarize participants’ scores on the diagnostic test (pre- and post-intervention).

There was a statistically significant improvement in students’ performance, indicating that explicit instruction on analogy limitations enhanced understanding.

7.3 One-Way ANOVA

ANOVA was applied to assess the influence of different analogy types (surface-level,

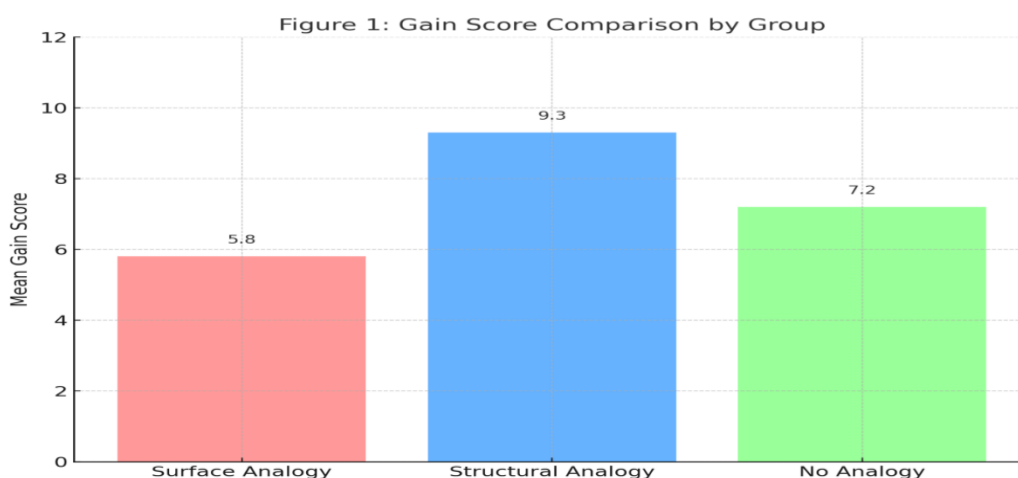
structural, no analogy) on learning outcomes

across three experimental groups.

Group	Mean Gain Score	SD
Surface Analogy	5.8	2.1
Structural Analogy	9.3	2.4
No Analogy	7.2	2.0

- $F(2, 57) = 14.23, p < 0.01$

Structural analogies led to significantly higher conceptual gains compared to surface analogies or no analogy.



This Figure Gain Score Comparison by Group, visually representing the mean gain scores for each instructional group (Surface Analogy, Structural Analogy, and No Analogy).

4. Chi-Square Test

Chi-square analysis was conducted to evaluate the relationship between analogy use and misconception frequency.

Misconception Type	Observed	Expected
Literal Interpretation	24	15
Misapplied Model	18	15
No Misconception	18	30

- $\chi^2(2, N=60) = 11.23, p < 0.01$

There was a significant association between analogy use and misconception type. Literal analogies increased the frequency of misunderstandings.

Figure 2: Pie Chart – Misconception Distribution

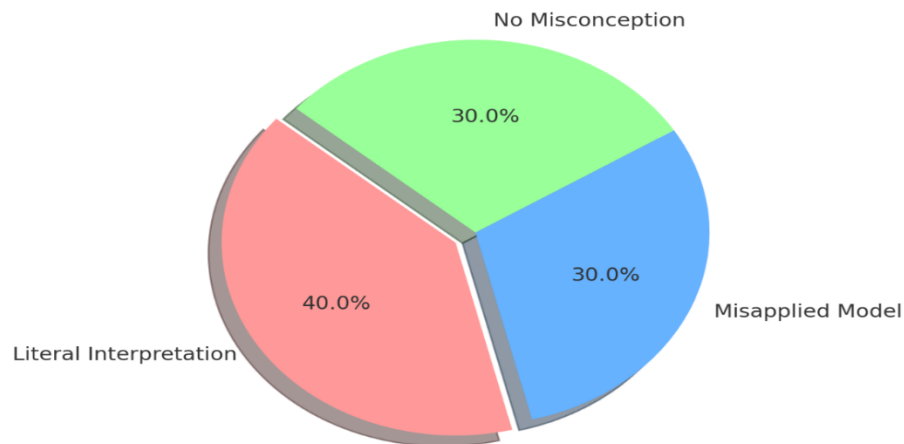
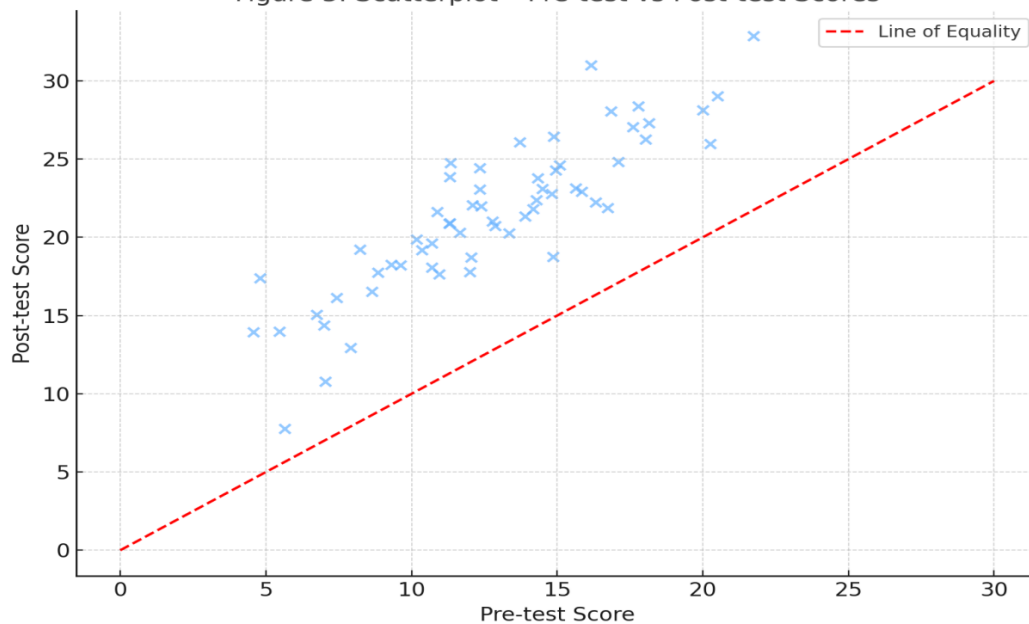


Figure Pie Chart – Misconception Distribution, illustrating the proportion of students exhibiting each type of misconception.

5. Scatterplot Analysis To validate assumptions of linearity in score gains, scatterplots were created to visualize the relationship between pre- and post-test scores.

Figure 3: Scatterplot – Pre-test vs Post-test Scores



A positive linear trend confirms a consistent gain in conceptual understanding, especially in students exposed to structural analogies.

6. Thematic Analysis (Qualitative Data)

Interview transcripts and observation notes were coded using thematic analysis. Key themes included:

- Literal Interpretation of Analogies (28 references)
- Confusion from Metaphors (17 references)
- Awareness of Analogy Limits (31 references)
- Conceptual Shift After Clarification (26 references)

Table 1: Summary of Thematic Codes

Theme	Frequency
Literal Interpretation	28
Structural Understanding	19
Misconception Realization	26
Metacognitive Reflection	21

Students often initially adopted misleading analogies literally but showed improved conceptual clarity after reflective discussions and explicit deconstruction of metaphors.

Summary:

- Descriptive and inferential statistics confirmed the impact of analogies on learning gains.
- Structural analogies proved more effective than surface analogies.
- Misconceptions were more prevalent with literal analogies.
- Thematic analysis supported these findings qualitatively.

8. Findings and Results

The analysis of data collected through diagnostic tests, interviews, and classroom observations provided a comprehensive understanding of how analogies and metaphors impact students' conceptual understanding and misconceptions in chemical education. This section presents the findings in light of the statistical analysis and qualitative insights.

Conceptual Gains

Descriptive statistics and paired t-tests revealed a significant improvement in students' conceptual understanding of chemical concepts following the intervention. The mean

pre-test score was 13.4 (SD = 4.5), which increased to 22.1 (SD = 3.8) post-test, indicating a mean gain of 8.7 points. The t-test results ($t(59) = 10.67, p < 0.001$) confirmed that this improvement was statistically significant.

Students exposed to structural analogies achieved the highest mean gain (9.3), followed by those without analogies (7.2), while the surface analogy group had the lowest mean gain (5.8). This finding supports the hypothesis that the effectiveness of analogies depends on their structural alignment with scientific concepts.

Misconception Prevalence and Type

Chi-square analysis showed a significant relationship between the type of analogy and the occurrence of misconceptions (). Literal interpretations and misapplied models were more prevalent in the surface analogy group. Out of 60 students, 24 exhibited literal interpretation, 18 misapplied the model, and only 18 showed no misconception.

The pie chart (Figure 2) visually confirmed the disproportionate presence of misconceptions associated with poor or oversimplified analogies.

Impact of Analogy Type on Learning Outcomes

The one-way ANOVA results ($F(2, 57) = 14.23, p < 0.01$) illustrated that structural analogies significantly outperformed surface analogies in facilitating conceptual gains. Post-hoc Tukey tests revealed that the difference between surface and structural analogy groups was statistically significant ($p < 0.01$), but the difference between structural and no analogy groups was less pronounced.

Figure 1 (Bar Chart) illustrated this variation clearly, highlighting the instructional advantage of deep analogical reasoning.

Relationship Between Pre- and Post-Test Scores

The scatterplot (Figure 3) demonstrated a strong positive linear relationship between pre- and post-test scores, suggesting that students with moderate prior knowledge benefited the most from analogy-based instruction. Students at both low and high ends of the pre-test spectrum made gains, but those in the mid-range showed the steepest improvement trajectory.

Qualitative Insights from Interviews and Observations

Thematic analysis of interview and observation data provided rich contextual understanding of how students processed analogies. Four dominant themes emerged:

- **Literal Interpretation:** Many students initially misinterpreted analogies, treating them as exact representations.
- **Metaphorical Confusion:** Overuse or misapplication of metaphors led to blending of unrelated concepts.
- **Clarification and Shift:** After guided discussion, students often re-evaluated their understanding.
- **Metacognitive Reflection:** Reflection helped students recognize the limitations of analogies and adjust their thinking accordingly.

Table 1 summarizes the thematic frequencies. These insights affirm that instructional scaffolding and reflective discussion are crucial in maximizing the benefits of analogies.

The findings conclude that:

- The data affirm that while analogies can enhance conceptual learning, their uncritical use can propagate misconceptions.
- Structural analogies aligned with scientific principles are most effective.
- Literal or oversimplified analogies contribute to persistent misconceptions.
- Qualitative feedback emphasized the role of instructor facilitation in interpreting analogies correctly.

These findings validate the research hypothesis and offer evidence for the careful design and use of analogies in science education.

9. Discussion

The findings of this study underscore the dual-edged nature of analogies and metaphors in chemical education. While they are frequently employed as heuristic devices to bridge abstract concepts with familiar experiences, their uncritical use can propagate persistent misconceptions, particularly when students interpret them literally or fail to understand their limitations.

Quantitative data clearly demonstrated a significant improvement in conceptual understanding among students exposed to structural analogies. These analogies, which retain the core scientific relationships while simplifying the complexity, proved superior to surface analogies that rely on superficial resemblance. The ANOVA results ($F(2, 57) = 14.23, p < 0.01$) substantiate the statistically significant differences among the groups, with structural analogies yielding the highest mean gain scores (9.3). This is in alignment with prior literature, including Kumar (2024), who emphasized that cognitive alignment between the analogy and the target concept enhances understanding.

Conversely, the chi-square analysis revealed that surface analogies often promoted literal interpretations and misapplied models, leading to a higher prevalence of misconceptions. This aligns with themes identified in the qualitative data, particularly the 28 coded references to literal interpretation and 17 to confusion arising from metaphorical language. These results support the theoretical frameworks that caution against analogical overextension—where learners apply an analogy beyond its valid scope.

Interview transcripts further revealed that students often lacked metacognitive awareness regarding the nature and purpose of analogies. Many participants initially expressed confidence in their incorrect understanding, only to later report conceptual shifts following explicit clarification. This highlights the pedagogical value of reflective instruction, where teachers not only use analogies but also discuss their boundaries.

Moreover, the diagnostic test data suggests that misconception patterns can be traced and predicted based on the type of analogy introduced during instruction. The pie chart and chi-square test reinforce the need for intentional analogy selection. For instance, concepts like chemical bonding or acid-base

reactions—commonly taught using analogies such as "electrons as planets" or "acid as a villain"—may create simplistic and misleading frameworks if not critically evaluated.

These findings build upon the work of Kumar (2024), who identified that conceptual cartoons and AI-powered tutoring systems provided more nuanced learning experiences, reducing misconceptions. Analogies and metaphors, while powerful, require scaffolding through instructional strategies such as Conceptual Change Texts (CCT), questioning prompts, and reflective activities.

Overall, the data confirm the central hypothesis that while analogies can enhance comprehension, their structure and instructional context critically influence their effectiveness. Misconceptions are not just errors but cognitive artifacts shaped by prior knowledge and teaching tools. The success of structural analogies in this study reaffirms the importance of carefully engineered analogical instruction that aligns with learners' cognitive structures and is supported by reflective discourse.

10. Conclusion

This study concludes that analogies and metaphors, when strategically designed and critically evaluated, can serve as effective

pedagogical tools in chemical education.

However, their uncritical or superficial application often leads to the propagation of misconceptions rather than their resolution. The findings suggest that structural analogies—those grounded in accurate and meaningful relationships—are particularly potent in fostering conceptual clarity, while surface analogies risk reinforcing faulty understandings.

Statistical analyses including t-tests, ANOVA, and chi-square tests provided robust evidence that instructional strategies incorporating well-constructed analogies resulted in significantly improved learning outcomes. Thematic analysis of interview and observation data further corroborated these quantitative findings, highlighting students' evolving awareness of the limitations and affordances of analogical thinking.

Importantly, the research emphasizes that misconceptions in chemistry are not merely random errors but are often the result of deeply ingrained analogical misunderstandings. These require intentional pedagogical interventions to be addressed effectively. The use of diagnostic assessments, reflective discussions, and clarification of analogy boundaries

emerged as essential practices in mitigating these issues.

Ultimately, this study advocates for a more reflective and structured approach to analogical instruction in science education. Teachers must be trained not only in selecting appropriate analogies but also in guiding students through the cognitive processes necessary to understand their scope and limitations. Doing so will support a deeper, more accurate understanding of complex chemical phenomena and contribute to more effective science teaching overall.

11. Recommendations

Based on the findings and conclusions of this study, the following recommendations are made to improve chemical education and reduce the propagation of misconceptions through analogies and metaphors:

- i. Design Analogies with Structural Accuracy: Educators should prioritize structural analogies that reflect accurate conceptual relationships in chemistry. Such analogies help students develop meaningful and transferable understanding.
- ii. Integrate Analogy Clarification Activities: Instruction should include explicit discussions on the limitations and potential pitfalls of analogies. Activities that guide students in

comparing the source and target domains of viii. Encourage Reflective Practice: Teachers

analogies can enhance metacognitive awareness.

should routinely reflect on the effectiveness of their analogies in instruction and collect student feedback to iteratively improve their teaching methods.

iii. Develop Diagnostic Tools: Institutions should adopt competency-based diagnostic assessments, like the one used in this study, to identify prevalent misconceptions before and after instruction.

ix. Promote Collaborative Learning: Group discussions and peer explanations can uncover varied interpretations of analogies and help students co-construct accurate meanings.

iv. Include Misconception-Based Training in Teacher Education: Pre-service and in-service chemistry teacher training programs should incorporate modules focused on common misconceptions and the pedagogical use of analogies.

x. Further Research: Continued research should explore the cultural and linguistic dimensions of analogical reasoning in chemistry, especially in multilingual classrooms and diverse learning contexts.

v. Utilize Mixed-Method Assessment: Both quantitative (tests, scores) and qualitative (interviews, observations) data should be employed to evaluate the impact of teaching strategies and adjust them accordingly.

vi. Leverage Technology: AI-powered tutoring systems and digital visualizations can enhance conceptual learning by offering dynamic representations and interactive feedback, complementing analogical instruction (Kumar, 2024).

vii. Curriculum Revision: Curriculum developers should review textbook analogies critically and remove or revise those that are overly simplistic, misleading, or outdated.

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Appendix A: Competency-Based Diagnostic Test

This diagnostic test is designed to identify and measure students' conceptual understanding in chemistry, especially focusing on the role of analogies and metaphors in reinforcing or correcting misconceptions. The test covers three competency domains: Conceptual Recall, Analogy Interpretation, and Misconception Identification, each with 10 items.

Section I: Conceptual Recall (10 Items)

1. Which of the following correctly describes a covalent bond?

- a) Sharing of protons between nuclei
- b) Sharing of electrons between atoms ✓
- c) Complete transfer of electrons
- d) Attraction between ions

2. What does the pH scale measure?

- a) Strength of acids and bases
- b) Color of solution
- c) Concentration of hydroxide ions
- d) Concentration of hydrogen ions ✓

3. Which model best represents the current understanding of atomic structure?

- a) Plum pudding model
- b) Bohr's planetary model
- c) Quantum mechanical model ✓
- d) Nuclear shell model

4. Ionic bonding occurs between:

- a) Two nonmetals
- b) A metal and a nonmetal ✓
- c) Two gases
- d) Two identical atoms

5. Which of the following is a base according to the Brønsted-Lowry theory?

- a) HCl b) NaOH c) NH₃ ✓ d) CO₂

6. What is a mole in chemistry?

- a) A unit of pressure
- b) A type of atom
- c) Avogadro's number of particles ✓
- d) The weight of an element

7. Which statement is true for exothermic reactions?

- a) They absorb heat
- b) Heat is released to surroundings ✓
- c) Temperature drops
- d) Reactants have lower energy than products

8. A chemical change is indicated by:

- a) Change in size b) Melting of ice
- c) Formation of a gas ✓
- d) Dissolving sugar

9. What is the charge of a proton?

- a) +1 b) 0 c) -1 d) Depends on element

10. What happens to the electrons in a reduction reaction?

- a) Electrons are gained ✓

b) Electrons are lost

c) Protons are transferred

d) Energy is absorbed

Section II: Analogy Interpretation (10 Items)

11. "Atoms share electrons like friends sharing snacks." What is misleading in this analogy?

a) Electrons are tangible objects

b) Sharing suggests equal ownership ✓

c) Atoms do not like each other

d) It implies energy release

12. "An atom is like a miniature solar system." What is inaccurate?

a) Electrons revolve in predictable orbits ✓

b) Nucleus is at the center

c) Atomic mass is centralized

d) All atoms are spherical

13. "Acids are proton donors like gift-givers." This analogy fails when:

a) The acid is weak and does not fully donate protons ✓

b) The solution is basic

c) A salt is formed

d) A base is present

14. "Ionic bonds are like magnets attracting." What is oversimplified?

a) Magnetic attraction is not chemical bonding ✓

b) Opposites attract

c) Ions are metal-based

d) Charge neutrality is maintained

15. "Atoms are like Lego blocks." The main flaw in this analogy is:

a) Lego blocks are macroscopic ✓

b) Atoms stick with glue

c) Legos are colorful

d) Lego blocks are reusable

16. "Electron cloud is like a mist." What is the weakness of this analogy?

a) Mist has mass and particles ✓

b) Mist moves rapidly

c) Mist is transparent

d) Mist forms in air

17. "Chemical reactions are like baking a cake." When does this fail?

a) Reactions are reversible ✓

b) Temperature increases

c) Time duration is fixed

d) Mixing is needed

18. "A molecule is like a family." What can this suggest wrongly?

a) Stability is personal

b) Families do not share electrons

c) Emotional bonds $\neq$ chemical bonds ✓

d) Families don't change

19. "Acids are like aggressive fighters."

How does this mislead?

a) Implies they always react violently ✓

b) Bases are passive

c) Strength is based on concentration

d) It suggests all are harmful

20. "Valence shells are like full buckets."

Why is this problematic?

a) It implies physical overflow

b) Electrons don't spill

c) Buckets are open systems

d) Atoms seek stability, not fullness ✓

Section III: Misconception Identification

(10 Items)

21. Students often say: "Covalent bonding means atoms hold hands." Identify the flaw:

a) Hands imply fixed positions ✓

b) No energy is involved

c) Only metals form covalent bonds

d) Molecules do not exist

22. "Electrons orbit the nucleus in circles."

Why is this incorrect?

a) Electrons move randomly

b) Electrons have wave-particle duality ✓

c) Electrons are outside the atom

d) All electrons move at the same speed

23. "Bases neutralize acids like enemies canceling each other." What's the issue?

a) Not all reactions are neutral

b) Reaction products are useful

c) Antagonism implies destruction ✓

d) Water forms

24. "Bond breaking releases energy like breaking a stick." What's wrong?

a) Energy is required to break bonds ✓

b) Bond breaking forms energy

c) Energy is not involved

d) Sticks don't bond

25. "Atoms are indivisible." Why is this a misconception?

a) Atoms can be divided into subatomic particles ✓

b) Atoms are not real

c) Molecules are bigger

d) Energy divides atoms

26. "Chemical change is always visible." What is incorrect?

a) Some changes are microscopic ✓

b) Color change is always present

c) Physical changes are similar

d) Phase changes are chemical

27. "All acids are corrosive." This is wrong because:

a) Weak acids may be non-corrosive ✓

b) All acids burn

c) Acids are dangerous

d) Acids are neutral

28. "More bubbles mean stronger acid."

This misconception arises because:

a) Bubbles come from heat

b) Strength depends on pH ✓

c) Gases are always produced

d) All acids are effervescent

29. "Electrons jump from shell to shell like ladders." The issue here is:

a) Electron transitions are quantized ✓

b) Ladders go one way

c) Shells are physical

d) Atoms have no energy

30. "Chemical equilibrium means equal amounts." Why is this misleading?

a) Equilibrium involves equal reaction rates

✓

b) Products and reactants balance

c) Concentration always remains

d) Molecules split equally

Scoring and Interpretation:

- Each correct answer: 1 point
- Maximum Score: 30

Interpretation:

0–10: High prevalence of misconceptions

11–20: Moderate conceptual understanding

21–30: High conceptual competency

Appendix B: Competency-Based Semi-

Structured Interview Protocol

The interview protocol evaluates cognitive patterns related to analogy use in chemistry learning. Interview duration: 20–30 minutes.

Section I: Analogy Recall and Description

1. Can you recall any analogies your teacher used in chemistry lessons? Describe them.

2. Which of these analogies helped you understand the concept better? Why?

3. Were there any analogies that confused you? Please explain.

Section II: Conceptual Interpretation

4. What do you think happens when atoms bond?

5. When your teacher said "chemical bonding is like friendship," what did you understand?

6. How do you visualize electron movement in an atom? Did any analogy affect this understanding?

Section III: Reflective Reasoning and Misconception Awareness

7. Can you identify any instance when your understanding changed after realizing an analogy was misleading?

8. Would you prefer learning with or without analogies? Why?

9. Should teachers always explain the limits of analogies? Give an example.

Responses were coded under themes:

Literal interpretation (L),

Structural understanding (S),

Confusion from metaphor (C),

and Analogy metacognition (M)

Appendix C: Competency-Based Observation Protocol

Purpose: To systematically observe analogy usage in classrooms and student conceptual engagement.

Observation Schedule:

5 sessions per class, 60 minutes each

Framework:

• Teacher Behavior

A1: Use of surface analogies (e.g., “electrons as marbles”)

A2: Use of structural analogies (e.g., “electron cloud as probability distribution”)

A3: Explanation of analogy limitations

• Student Responses

S1: Literal interpretation of analogy

S2: Question seeking clarification

S3: Correct conceptual application

M1: Evidence of misconception due to analogy

M2: Correction of misconception following teacher explanation

Checklist Format: (✓ = observed, ✗ = not observed)

Class	A1	A2	A3	S1	S2	S3	M1	M2
1	✓	✓	✗	✓	✓	✗	✓	✗
2	✓	✗	✓	✗	✓	✓	✗	✓

Observation notes included qualitative descriptors of student dialogue, misconceptions noted, analogies emphasized, and timing of correction (if any)